Effect of Electropulsing on Recrystallization of Fe-3%Si Alloy Strip

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Recrystallization and microstructural changes of an electropulsing treated (EPT) Fe-3%Si alloy strip were studied using optical microscopy and electron backscattering diffraction (EBSD) techniques. Microstructural evolution and misorientation angle distribution were detected during recrystallization in both EPT and traditional heat treated (THT) alloy specimens. The results indicate electropulsing tremendously accelerated movement of dislocation and vacancies, which is in favors of recrystallization. The temperature of recrystallization was reduced. A sufficient high temperature became a dominant factor in speeding up recrystallization. The mechanism of electropulsing induced recrystallization is discussed from the point view of dislocation dynamics, microstructural changes and electropulsing kinetics.

Grain-oriented Fe–3% Si steels are used as cores in electrical transformers due to their soft magnetic properties. In order to develop a new production technology for grain-oriented silicon steel heat treatment, EPT is use to cold rolling Fe–3% Si strip. As an alternative to the traditional thermal and mechanical processes, EPT has been recognized for its high efficiency and attracted attention for use in extensive studies in materials science and engineering, such as electroplasticity,1–4) electromigration,5) recrystallization,6) phase transformation 7–11) and mechanism of interaction between electrons and lattice atoms and dislocation movement.12,13) In our previous studies indicated that EPT enhanced rates of recrystallization of AZ31 alloy.14) Compared with the conventional processes, microstructure and grain size were remarkably different, and the material properties were improved. But so far little has been done on the effects of electropulsing on the microstructural evolution of the Fe-Si alloy.

The material selected in the research was a commercial Fe-Si alloy with a composition of Al(0.024 mass%), N(0.026 mass%), Cu(0.10), Si(3 mass%), Fe in balance. The as-received Fe-Si alloy strip of 6 mm in width and 0.3 mm in thickness was produced after 75% final reduction of cold rolling at room temperature. The schematic view of EPT process is shown in Fig. 1. Multiple pulses current generated continuously are applied to the alloy strip directly when the Fe-Si alloy strip was moving at a speed of 1 m/min through a distance of 200 mm between the two electrodes. An electropulsing generator was applied to discharge positive-directional multiple pulses with various pulse voltage through adjusting controlling parameters. It took about 12 s to move the strip from anode to cathode. An infrared thermoscope was adopted near the cathodes to test the surface maximum temperature of material directly. The current parameters such as amplitude and root-mean-square density values and frequency can be monitored by a Hall-effect sensor connected to an oscilloscope. Compared with the EPT, the traditional heat treatments were carried out for the same Fe-Si alloy strip in the furnace at various temperatures. The EPT and the THT both carry out under the natural air circumstance. The parameters of EPT and THT are separately listed in Table 1 and in Table 2.

Longitudinal cross sections of both EPT and THT specimens were well polished and examined using scanning microscopy in the EBSD and the conventional optical microscopy.
Shown in Fig. 2 are optical images of the as received Fe-Si alloy strip (a), specimens after THT at 680 °C (b), 850 °C (c), and 1200 °C (d). A typical microstructure of prolonged crystals along rolling direction is observed to be mixed with a large number of shear bands resulting from intensified strains, as shown in Fig. 2(a). After THT at 850 °C, the recrystallization was well developed with grain size of about 17 μm in diameter (Fig. 2(c)). With increasing temperature to 1200 °C, the grains grew gradually. The grain size increased to 40 μm.

The microstructures of EPT specimens are shown in Fig. 3. Under electropulsing, the recrystallization was accelerated. As shown in Fig. 3(a), partial recrystallization was observed after 74.0 V EPT at 510 °C. The recrystallization was well developed after 77.5 V EPT at 750 °C, the grain size was about 15 μm in diameter, as shown in Fig. 3(b). When the pulse voltage increased up to 79 V at 850 °C, the grains grew gradually and the grain size increased to about 20 μm in diameter. Compared the 77.5 V-750 °C EPT state (Fig. 3(b)) with the THT state at 850 °C (Fig. 2(c)), it can be seen that the recrystallization temperature in the EPT specimens decreased about 100 °C. It was surprising to observe that the grains size of the specimen dramatically increased to about 230 μm in diameter after 82.5 V at 1200 °C. This means that under electropulsing at 1200 °C, the recrystallization was tremendously speeded up.

In order to study microstructural evolution and misorientation angle distribution, ENSD examination was carried out on both THT and EPT specimens. Shown in Fig. 4 are EBSD Euler distributions and misorientation angle distributions of the specimens after THT at 750 °C (Figs. 4(a) and 4(b)) and 850 °C (Fig. 4(c) and 4(d)), respectively. A small amount of low angle grain boundaries (<10°) were existed in both specimens after THT at 750 °C and 850 °C. Those low angle grain boundaries were found at the grain boundaries and inside the grains, as indicated by white lines in Fig. 4(a) and (c). A small amount of the misorientation angle distributions are shown in Fig. 4(b) and (d).

The EBSD Euler distribution and the misorientation angle distribution of the specimens after 77.5 V-EPT at 750 °C and 79 V-EPT at 850 °C are shown in Figs. 5(a) and (c) and Figs. 5(b) and (d), respectively. Compared with the THT specimens, the low angle grain boundaries were increased at the grain boundaries and inside the grains, as indicated by white lines in Fig. 5(a) and (c). The amount of the misorientation angle distributions are apparently enhanced, as shown in Fig. 5(b) and (d).

The driving force for recrystallization in the EPT alloy specimens can be understood from following two parts: $\Delta G_{\text{EPT}} = \Delta G_{\text{thermal}} + \Delta G_e$, where $\Delta G_{\text{thermal}}$ is the Gibbs free energy resulting from Joule heat. $\Delta G_e$ is the electropulsing-induced Gibbs free energy, which is strongly related to the crystal orientation. In a current-carrying system, $\Delta G_e$ can be described as follows:\textsuperscript{15}

$$\Delta G_e = \mu_g g^2 (\sigma_1, \sigma_2)^2 \Delta v$$

(1)

$$\xi(\sigma_1, \sigma_2) = (\sigma_2 - \sigma_1)/(\sigma_1 + 2\sigma_2)$$

(2)

where $\mu_g$ is the magnetic susceptibility in vacuum, $g$ a positive geometric factor for coarse grained materials, $j$ the current density, $\Delta v$ the volume of a nucleus and $\xi(\sigma_1, \sigma_2)$ is a factor which depends on the electrical properties of the
nucleus and the matrix, $\sigma_1$ and $\sigma_2$ are the electric conductivities of the different grain, respectively.

As well recognized, low angle grain boundaries (<10 degree) are those which to be composed of arrays of dislocations. Electropulsing accelerated dislocation movement. A large number of dislocation piled up and blocked at the grain boundaries and at the structural defects, such as dislocations, vacancies and precipitates etc. inside the grains, where accumulated a great deal of strain energy.\(^{35}\) The identity of the dislocation was reduced when the low angle boundaries increased in EPT specimens, as shown in Fig. 5. Both the high energy storage in those low angle boundaries and poor dislocation identity affected greatly the conductivity as well. Eventually differences in conductivity, $(\sigma_1-\sigma_2)$,
between the grains increased as $\xi$ increased. As a result, $\Delta G_e$ increased, which was in favor of recrystallization and the temperature of recrystallization reduced.

Previous studies indicated that under electropulsing electron wind formed by the knock-on collision of high-rate electrons with atomic nuclei was beneficial to the mobility of dislocation.\textsuperscript{13) Under the impact of transient stress, motivated dislocations were moving very quickly, even at ultrasonic speeds.\textsuperscript{16) The transfer of energy from the electrons directly to the atoms was much more effective than that in the traditional thermal and thermo-mechanical processes.

It was supposed that the electropulsing affected effectively the sliding behavior of the dislocation, and the activity of vacancies.\textsuperscript{13) As far as the recrystallization process by EPT, it is anticipated that electron migration may be important when considering the influence of an electric current. The effect of the atomic diffusion flux, $J$, on the motion of vacancies and dislocation to the grain boundaries are important.

The effect of electric current on the atomic drift flux of atoms in metals is given by Nernst–Einstein equation.

$$J_i = \frac{N_i \cdot D_i}{K^T} \left( KT \cdot \frac{\partial \ln X_i}{\partial x} - \Omega \cdot \frac{\partial \sigma}{\partial x} + Z^* \cdot e \cdot \rho \cdot j \right)$$  \hspace{1cm} (3)

where $N_i$ is the density of the $i$ atom species, $D_i$ the pertinent diffusion coefficient, $Z^*$ the effective valence, $e$ the charge on an electron, $\rho$ the resistivity, $j$ the current density, $\sigma$ the stress, $K$ the Boltzmann constant, $\Omega$ the atomic volume, $X_i$ the concentration of the $i$ solute, $G$ atom volume, $\frac{\partial \ln X_i}{\partial x}$ the stress gradient, $K$ the Boltzmann constant, $T$ the absolute temperature.

The effects of chemical potential gradient and composition gradient mentioned in eq. (3) were neglected here since these effects were much weaker than that of electropulsing. In the case of electropulsing, the $J$ consists of two parts: $J_1$ and $J_2$, where $J_1$ is the flux of diffusion atoms due to the thermal effect and $J_2$ is the flux of the diffusion atoms owing to the athermal effect.

The average atomic flux per second during multiple continuous electropulsing can be described in eq. (4).\textsuperscript{17)

$$J = J_1 + J_2 = \frac{2\pi D_o}{\Omega \ln \left( \frac{K}{\gamma_0} \right)} \left( 1 + \frac{\delta_c}{c_o} \right)$$

\[+ \frac{2N \cdot D_l \cdot Z^* \cdot e \cdot \rho \cdot f \cdot j_m \cdot \tau_p}{\pi KT} \] \hspace{1cm} (4)

where $D_l$ is the lattice diffusion coefficient, $c_o$ the average concentration of vacancy, $\delta_c$ supersaturation concentration of vacancies, $\Omega$ atom volume, $\gamma_0$ and $R$ the distance far from dislocation where the vacancy concentrations are $c_0$, $\gamma_0 + \delta_c$, respectively; $N$ is the density of atom, $Z^*$ an effective valence, $e$ the charge on an electron, $\rho$ the resistivity, $K$ the Boltzmann constant, $T$ the absolute temperature; $j_m$, $f$ and $\tau_p$ are peak current density, frequency and duration of each electropulse, respectively.

The second part of the eq. (4) represents the athermal effect. When the temperature of the specimen is low, $J_2$ is small and neglected. Then the atomic flux for the recrystallization, $J_a$, is strongly dependent on the parameters of electropulsing, and increases remarkably with the peak current density, frequency $f$, duration of each electropulse $\tau_p$, peak current density $j_m$ and the duration of EPT $t_{ept}$, when the temperature $T$ is constant.

The dislocations climbing into the subgrain boundaries has close relationship with the total flux of the diffusing atoms ($J$). Under electropulsing, a high peak current density is sufficient to accelerate an active climb of dislocations, and plays a important role in nucleation. From Fig. 2(b) and Fig. 3(b) it can be seen that the EPT decrease recrystallization temperature is decreased.
From the first part of the eq. (4), it can be seen that with increasing the voltage of EPT, the supersaturated concentration of vacancies (i.e. \(\xi_c\)) enhanced, because those low angle boundaries with high energy storage resulted in the poor identity of dislocation in the EPT specimens. 3) The thermal effect, \(J_t\) became a dominant factor in accelerating recrystallization at high temperature. That is why the grain size was significantly increased in the EPT specimen at 1200°C, as seen in Fig. 4(d).

In summary, the following conclusions are drawn:
(1) Electropulsing resulted in increasing the high energy storage at the low angle boundaries and reducing dislocation identity. As a result, the electropulsing induced driving force for recrystallization, \(\Delta G_e\) increased. Recrystallization was speeded up greatly and the temperature of recrystallization reduced.
(2) Under electropulsing with high temperature, the thermal effect, the electropulsing induced \(\Delta G_{\text{thermal}}\), became a dominant factor and the driving force for recrystallization considerably increased.

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REFERENCES